Alternative nitrogen management practices to reduce carbon footprint of maize production

Mattia Fumagalli[1*]

Abstract: *Intensive maize production in Lombardy region (northern Italy) is widespread and requires big amounts of input, especially nitrogen (N), thus leading to potential environmental risks. Starting from farm survey data the current work aims to evaluate how alternative N management options for reducing losses can be effective in climate change mitigation. Under current management (ACT) of typical continuous maize cropping systems across the region, the greenhouse gases (GHG) emissions from the production of inorganic fertilisers and from direct and indirect* N_2O *released after N application accounted for, on average, 67% of the total GHG emissions. The adoption of the best N management plans (FERT scenario), reduced GHG emissions and C-footprint (expressed per unit of agricultural product) by 27 and 26%, respectively. Furthermore, the double cropping system (two crops harvested in 12 months - ROT scenario) strongly increased GHG emissions in comparison with the only cultivation of a summer crop. However, the high productivity of this system, led to a C-footprint lower than the ACT one and still higher than the FERT one. The current work highlights the opportunities for carbon mitigation offered by changes on field N management, without significantly impact the yield.*
Keywords: *carbon footprint, crop rotation, fertilisation, greenhouse gas emission, nitrogen, maize crop.*

Riassunto: *I sistemi maidicoli intensivi della Regione Lombardia (nord Italia) sono molto diffusi e il livello richiesto dei fattori di produzione, su tutti l'azoto, è decisamente alto, determinando così potenziali rischi per l'ambiente. Questo lavoro, per cui sono stati usati dati ottenuti da monitoraggi condotti su diverse aziende, si pone l'obiettivo di valutare come una gestione alternativa dell'azoto, mirata a ridurne le perdite, possa contribuire alla mitigazione del cambiamento climatico. Per quanto riguarda la gestione corrente di monosuccessioni di mais (scenario ACT), il 67% delle emissioni di gas ad effetto serra è associato alla produzione di fertilizzanti chimici e all'emissione diretta e indiretta di protossido di azoto, causata dalla distribuzione di fertilizzanti azotati. L'adozione di corretti piani di concimazione nello scenario FERT, ha invece determinato una riduzione delle emissioni e dell'impronta di carbonio pari al 27 e 26%, rispettivamente. Il sistema a doppia coltura (due colture raccolte in 12 mesi), caratteristico dello scenario ROT, ha invece causato un aumento delle emissioni rispetto alla coltivazione di una sola coltura primaverile-estiva. L'elevata produttività di questo sistema, ha permesso di ridurre l'impronta di carbonio rispetto a ACT, mantenendosi tuttavia ancora inferiore a FERT. Questo lavoro ha evidenziato che esistono gestioni alternative dell'azoto che consentono di far fronte almeno parzialmente al problema del cambiamento climatico, senza influenzare in maniera rilevante la produttività.*
Parole chiave: *impronta di carbonio, rotazione colturale, fertilizzazione, emissione di gas serra, azoto, mais.*

1. INTRODUCTION

Agricultural activities adversely affect the environment in several ways, causing the loss of nutrients, sediments and plant protection products (PPPs) to surface and ground waters, air pollution, fossil fuel exploitation, water depletion and greenhouse gases emissions (GHG), mainly carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). In particular, GHG emission is a crucial factor, due to the global warming potential of the above-mentioned gases contrasting with the ambitious environmental targets established by policy makers. The 20:20:20 climate-energy package approved by the European Union in 2008 established the specific target of 20% reduction in GHG emissions from 1990 levels by 2020. Later, the Decision No 406/2009/EC decreed to go further and commit to a 30% cut. Interesting results have been recently found by Tubiello *et al.*, (2013) who showed declines of GHG emission from agriculture in Europe during the 1961-2010 reference period in comparison with other continents. However, Smith (2012) pointed out that, although the technical potential for mitigation by 2030 from European agriculture was estimated to be significant (about 200 Mt CO_2 per year), several barriers and constraints to full implementation of GHG mitigation measures remain.

In 2010, the agricultural sector in Lombardy region (northern Italy) produced approximately more than 7.000 kt of CO_2 equivalent emissions (CO_2eq)

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corresponding to the 9% of the total regional emissions (INEMAR, 2010). Agricultural soils are known to be the greatest single source of N_2O direct emissions accounting for the 80% of the anthropogenic emissions (INEMAR, 2010), because of the use of mineral N fertilisers and animal manure (van Groeningen *et al.*, 2010). Moreover, the agriculture uses energy for machinery and manufacturing inducing high levels of CO_2 emissions.

The term C-footprint usually defined as a unit of CO_2 equivalent emitted per unit of product (e.g. kg CO_2eq per kg of dry product) has been introduced to quantify the GHG emission impact on environment. Studies aimed to assess the effect of arable crop production practices on C-footprint are quite new (Adler *et al.*, 2007; St Clair *et al.*, 2008; Hillier *et al.*, 2009, 2011; Cheng *et al.*, 2011, 2014; Gan *et al.*, 2011a, b; Rajaniemi *et al.*, 2011; Knudsen *et al.*, 2014) and only a few are focused on analysing the impact of different maize production managements (Adviento-Borbe *et al.*, 2007; Ma *et al.*, 2012; Jayasundara *et al.*, 2014). A less impactful agronomic practices are suggested by Smith *et al.*, (2008) to reduce the emission of GHG and the C-footprint from cropland production: adjusted N fertiliser rates, diversified cropping systems, reduced tillage and accurate residue and water managements. Moreover, Mhamuti *et al.*, (2009) underline that a positive contribution on GHG emission reduction can come from the crop disease control.

Maize crop (*Zea mays* L.) both for grain and silage use is widely grown up in Lombardy region: more than 50% of the utilisable agricultural area of the plain, namely 380.384 ha, is devoted to such crop (ISTAT, 2012). Maize it is commonly cultivated in continuous mono-cropping system and it is characterized by high average yields: 10.5 and 20.2 t DM ha-1 for grain maize and silage maize, respectively (ISTAT, 2012). Consequently high levels of N fertilisers, PPPs for a regular control of weeds, and irrigation water (mainly applied with surface and sprinkler methods) are commonly requested to grant these yields. The abundant use of inorganic and organic fertilisers results in N surplus and consequently in losses in water and atmosphere, as previously quantified by others Authors (Bechini and Castoldi, 2009; Fumagalli *et al.*, 2011; Perego *et al.*, 2012; Carozzi *et al.*, 2013). Moreover, tillage is carried out mostly by ploughing and harrowing, causing a considerable exploitation of non-renewable energy sources (Fumagalli *et al.*, 2011); on the contrary minimum and no tillage practices are rarely adopted.

In the current work, GHG emission and C-footprint from typical continuous maize cropping systems were estimated using farm survey data, under current and alternative managements which include the reduction of N fertilisers rates and the introduction of the double cropping systems (two crops harvested in 12 months) with maize and autumn-winter crops. Therefore, the main objective was to assess the impact of different solutions for reducing N losses on climate change mitigation.

2. MATERIALS AND METHODS

2.1. Data sources

Data were taken and opportunely integrated, as part of a farm survey carried out across Lombardy region, aiming to evaluate and optimise the management of representative farming and cropping systems, providing recommendations for improving N management (Fumagalli *et al.*, 2011).

Five dairy and arable farms, representative in term of pedo-climatic conditions and management features, were preliminary selected. Secondly, continuous maize cultivations for both silage (SM) and grain (GM), were taken into account for carbon footprint estimation. The following management information were available: tillage, sowing, irrigation, fertiliser and manure application, PPPs application, harvest, and the crop yield. Moreover, the tractor-implement combinations for each individual crop operation were available. The management configuration of GM and SM recorded during the survey and corresponding to the average farmer's behaviour over several years, was labelled as "actual scenario" (ACT). Maize types and management corresponding to one or more farm fields are presented in Tab. 1. The farm survey dataset covered a wide range of conditions: i) the average annual rainfall ranged from 696 to 1150 mm year^{-1}; ii) the soil texture ranged from sandy to clay loam; iii) the average annual nitrogen application from organic and inorganic fertilisers ranged from 200 to 304 and from 11 to 307 kg ha^{-1}, respectively; iv) the applied fertilisers included dairy manure (liquid and solid), pig slurry, ammonium nitrate, urea and nitrogen compounds; v) broadcast-applied manure and its incorporation in the soil with ploughing within 24 - 72 hours after application, is the most common technique; vi) the sowing and harvesting dates for maize (both for silage and for grain) extended from March to April and from August to October, respectively; and vii) sprinkler irrigation was performed with amounts of about 325 mm and border irrigation was carried out with amounts ranging from 320 to 430 mm. Because of the higher amount of natural precipitation, one case occurs in which maize was not irrigated.

Due to the high levels of N applied to maize crop through inorganic and organic fertiliser application, two alternative N management were elaborated to reduce soil surface N balance and consequently N losses

Farm	Field	Scenario	Crop	Fertilisation (kg ha^{-1}) Mineral N	Organic N	P_2O_5	K_2O	Lime	Crop Yield (t DM ha^{-1})
A	1[1]	ACT	SM	307	288				21.5
		FERT	SM	46	288				21.5
		ROT	SM		288				18.0
			SW	88	144				12.0
B	1	ACT	SM	138	304				20.0
		FERT	SM	100	268				20.0
		ROT	SM		236				16.0
			IR	30	83				6.4
	2	ACT	GM	138	304				10.2
		FERT	GM	80	268				10.2
		ROT	GM		236				7.7
			IR	30	83				6.4
C	1	ACT	SM	196	301	94	156		20.5
		FERT	SM		301	94	156		20.5
		ROT	SM		301	94	156		16.0
			IR		196				7.0
D	1[2]	ACT	SM	211	200	138		300	15.0
		FERT	SM	110	200	138		300	15.0
		FERT1	SM	110	160	138		300	15.0
	2[2]	ACT	SM	211	200	138		300	15.0
		FERT	SM	110	200	138		300	15.0
		ROT	SM	52	160	138		300	12.5
			ST	180	100				8.8
	3	ACT	SM	211	110	138		300	15.0
		FERT	SM	110	110	138		300	15.0
E	1[2]	ACT	SM	11	239	25		300	18.7
		ROT	SM	11	243	25		300	16.4
			IR	134	73				8.0

IR= Italian Ryegrass; GM= Grain Maize; SM= Silage Maize; SW= Silage Wheat; ST= Silage Triticale
In D farm the maize is rainfed, elsewhere is irrigated
[1]Crop fertilised with digestate
[2]Crop fertilised with solid manure

Tab. 1 - Main information used in the estimation of GHG emissions and C-footprint for maize-based cropping systems under the three scenarios.
Tab.1 - Principali informazioni utilizzate per il calcolo delle emissioni di gas a effetto serra e dell'impronta di carbonio dei sistemi maidicoli per i tre scenari.

(Fumagalli *et al.*, 2012). The first one (FERT) was an improvement of the current fertiliser management scheme through the application of a nutrient management plan (NMP) not used in ACT by farmers, aimed at maintaining the same maize yields. Comparing inputs and outputs of N (mass balance) based on yield target, soil N mineralisation, estimated recovery of applied N, and manure N content, the mineral N dose to meet the crops N need has been found. When preparing the NMP the following rules has been considered: i) the manure produced on-farm was completely used on farm fields; ii) the manure was

redistributed among crops N uptake; iii) the manure was preferably applied in spring and not in autumn if the soil type allowed it; and iv) the use of chemical N fertilisers (e.g. the pre-sidedress mineral N application on maize) was reduced.
The second solution (ROT) was characterised by the introduction of a double cropping system with maize and autumn-winter crops, namely Italian ryegrass (*Lolium multiflorum* Lam.), silage wheat (*Triticum aestivum* L.) and triticale for silage (*x Triticosecale* Wittmack) in order to increase N uptake when the most leaching occurs. As before, the N amount was calculated by compiling a NMP. For autumn-winter crops N fertilization was scheduled in two applications, prior to planting with organic manure and as a top dressing with inorganic fertiliser. FERT scenario was not performed where N management was considered already adequate in ACT.
Crop yields according to the new fertilisation scheme and crop rotations adopted in the alternative scenarios were predicted by using the cropping system simulation model CropSyst (Stöckle *et al.*, 2003), already parameterised and evaluated in northern Italy for maize-based cropping systems (Donatelli *et al.*, 1997; Morari *et al.*, 2004; Bechini *et al.*, 2006, 2008; Fumagalli *et al.*, 2013). CropSyst was run for a period of 18 years using daily meteorological data (1990 - 2007) provided by the weather station closest to each farm. When the yield predicted by the model under FERT scenario was lower than under ACT, the amount of mineral N was adjusted until the two simulated yield were equal. Details on the procedure used for defining the alternative scenarios are available in Fumagalli *et al.*, (2012).
Tab. 1 summarises the main information of the maize-based cropping systems, corresponding to the three scenarios.

2.2. GHG emissions and C-footprint estimation

The GHG emissions of maize production was estimated according to the common methodology as the sum of CO_2 equivalent emissions from (a) the decomposition of crop residues (straw and roots), (b) the application of inorganic and organic N fertilisers, (c) the production, storage and transportation of N, P and K fertilisers, (d) the production of PPPs namely herbicides, fungicides, and insecticide and (e) various field operations including tillage, sowing, fertilisers distribution, spraying PPPs, irrigation, harvesting products, transportation of machinery and products from farm to field and vice versa. In addition, the contribution of seed production to the emission was considered.
The emissions of N_2O resulting from managed soils occur directly from the soils to which the N is added/released, and indirectly through ammonia volatilisation and nitrate leaching (IPCC, 2006).
The direct soil N_2O emissions (N_2O_{drt}) from the application of inorganic (N_{IF}) and organic (N_{OF}) N fertilisers and crop residues (N_{CR}) were estimated as follow:

$$N_2O_{drt} = (N_{IF} + N_{OF} + N_{CR}) \times EF \times \frac{44}{28} \tag{1}$$

where EF is the emission factor and 44/28 is the coefficient converting N_2O-N to N_2O. The IPCC methodology (IPCC, 2006) suggests a default emission factor equal to 0.01 that, however, does not consider the environmental conditions affecting N_2O emissions. Therefore, it was used the Canadian-specific method developed by Rochette *et al.*, (2008) that estimates the EF as a function of the growing season moisture deficit represented by the ratio of precipitation (P) to evapotranspiration (E):

$$EF = 0.022 \times \frac{P}{E} - 0.0048 \tag{2}$$

The reference evapotranspiration was calculated using the Priestley-Taylor model (Priestley and Taylor, 1972) starting from meteorological data (Fumagalli *et al.*, 2011).
Crop residues were considered as a source of N denitrification and nitrification assuming that the N contained was released as N_2O in the same year of production (Ma *et al.*, 2012). To quantify the N from crop residues was taken into account the above (straw) and belowground (roots) biomass by its respective N concentration (Fumagalli *et al.*, 2011). The ratio of belowground residues to above-ground biomass and the N content of below-ground residues were obtained from the results of CropSyst model.
The indirect soil N_2O emissions (N_2O_{indrt}) from nitrate leaching and volatilisation of NH_3 were estimated as follows:

$$N_2O_{indrt} = [(N_{Leach} \times EF_{Leach}) + (N_{IF} \times FRAC_{Gasf} \times EF_{VD}) + (N_{OF} \times FRAC_{Gasm} \times EF_{VD})] \times \frac{44}{28} \tag{3}$$

where EF_{Leach} and EF_{VD} are the emission factors for leaching and volatilisation, respectively, $FRAC_{Gasf}$ and $FRAC_{Gasm}$ are the fraction of N_{IF} and N_{OF} that volatiles as NH_3-N, respectively, and NLeach is the N subject to leaching. The fraction of N applied that volatilises from livestock manure was derived with the support of the regression-model ALFAM which provides the total cumulated emission as % of the total ammoniacal N applied (Søgaard *et al.*, 2002). The volatilisation from all the inorganic fertilisers applied was assumed as the 4% of the total N applied, according to results

experimentally found by Carozzi (2011) for urea applications. The amount of N leached for each scenario was predicted by running CropSyst as above specified.
All emission factors, compliant with the 2006 IPCC Guidelines (IPPC, 2006) and the climatic variables considered are reported in Tab. 2.
The N_2O emissions were converted into emissions of CO_2 equivalent by using a Global Warming Potential (GWP) of 310 over a 100 years' time horizon as recently done in some papers (Gan *et al.*, 2011a, b; Ma *et al.*, 2012).
CO_2 emissions from farm activities derive directly from combustion of fuel consumed during field operations, and from urea and lime applications, or indirectly from fertilisers, PPPs and seeds manufacturing. The emissions associated with agronomic operations were estimated through a mechanization model (Lazzari and Mazzetto, 1996; Fumagalli *et al.*, 2011), able to evaluate the machinery performances using a data set obtained on-farm (tractor-implement combinations actually used; distance, area and shape of each treated field; crop yield). The model estimates the consumption of fuel, and the total work time required for each operation carried out on field. To assess the actual emission, a conversion factor of 2.64 kg CO_2 equivalent per litre of fuel was used.

The addition of urea to soils during fertilisation leads to a loss of CO_2 estimated as follows:

$$CO_2eq_{urea} = N_{IF-urea} \times \frac{44}{12} \times \frac{12}{28} \qquad (4)$$

where $N_{IF\text{-}urea}$ is the amount of N distributed as urea, 12/28 is the ratio of C to N and 44/12 is the coefficient converting CO_2-C to CO_2.
Application of agricultural lime as fertiliser was assumed to cause a CO_2 emission equal to:

$$CO_2eq_{lime} = M_{lime} \times EF_{lime} \times \frac{44}{12} \qquad (5)$$

where M_{lime} is the amount of lime distributed, EF_{lime} is the default emission factor equal to 0.12 (IPCC, 2006).
In order to sustain maize production, PPPs were applied and consequently the coefficient of 0.069 kg CO_2 equivalent per MJ of PPPs was used to convert the energy content to the GWP (Audsley *et al.*, 2009). The embedded energy was estimated by using energy equivalents derived from the literature review (Bechini and Castoldi, 2009). In the current work emissions from production, transportation, storage, and transfer of N, P and K fertilisers to farm fields were estimated as the amount of N, P_2O_5 and K_2O multiplied by average emission factors of 4.8, 0.73 and 0.55 kg CO_2eq kg^{-1}, respectively (Lal, 2004). The CO_2 emissions from seed production were estimated by multiplied the amount of seed used by emission factors proposed by West and Marland (2002).

Variables	Farm				
	A	B	C	D	E
Precipitation of maize growing season (mm)[1]	409	485	623	376	548
Reference evapotranspiration of maize growing season (mm)[2]	907	889	801	903	882
Precipitation of winter crop growing season (mm)[1]	365	211	390	774	339
Reference evapotranspiration of winter crop growing season (mm)[2]	196	232	237	121	237
Ratio of P:E of maize	0.45	0.55	0.78	0.42	0.62
Ratio of P:E of winter crop[3]	1.82	0.91	1.65	1.43	6.40
Emission factor of maize (EF) kg N_2O-N kg^{-1} N	0.0051	0.0072	0.0123	0.0044	0.0089
Emission factor of winter crop (EF) kg N_2O-N kg^{-1} N	0.0172	0.0152	0.0172	0.0172	0.0172
Leaching (N_{leach}) kg N	Estimated by CropSyst model				
Volatilisation of NH_3 for inorganic fertilisers ($FRAC_{Gasf}$) %	0.04				
Volatilisation of NH_3 for organic fertilisers ($FRAC_{Gasm}$) %	Estimated by ALFAM model				
Leaching emission factor (EF_{Leach}) kg N_2O-N kg^{-1} N	0.0075				
Volatilisation emission factor (EF_{VD}) kg N_2O-N kg^{-1} N	0.01				

Maize growing season: April-September; Winter crop growing season: October – March
[1] Measured meteorological data (1990-2007)
[2] Estimated cumulative value of the regional area where farm is located (from Fumagalli *et al.*, 2011)
[3] For farm A, C, D, E the ratio of P:E for winter crop growing season was set to 1 to estimate EF which values reached the upper limit (Rochette *et al.*, 2008)

Tab. 2 - Climatic conditions, parameters and emission factors used in the estimation of N_2O emissions.
Tab. 2 - Condizioni climatiche, parametri e fattori di emissione utilizzati per la stima delle emissioni di N_2O.

Since the double cropping system in ROT scenario is defined as two crops harvested in a year, total GHG emissions and crop biomass were calculated by summing both crops values.

Total GHG emissions were expressed as kg CO_2eq per hectare per year. The C-footprint of maize production was expressed as kg CO_2eq per kg of dry product, namely grain yield in case of grain crop and above-ground biomass in case of silage crop.

3. RESULTS

3.1. Overall GHG emissions and C-footprint for the current maize management

Under the ACT scenario, the GHG emission varied from 2838 to 6460 kg CO_2eq ha^{-1} (Tab. 3, Fig. 1 and 2). The 50% of the total emission was derived from fertiliser N application and the maximum value was detected in the field C1 (4000 kg CO_2eq ha^{-1}). A discrete portion of such emissions was induced by leaching and volatilisation, which simulated values ranged from 15 to 195 and from 25 to 80 kg N ha^{-1}, respectively.

Emissions from production, transportation and delivery of main production factors such as fertilisers, PPPs and seeds, accounted for 23% with a minimum value of 8% in the field E1, where few inorganic fertilisers were used. Among these production factors, the release from N fertilisers was the greatest one, representing the 90% of the total, on average.

The CO_2 emissions determined by field operations accounted for, on average, 21% of the total GHG

Farm field	Scenario	GHG Emissions from (kg CO_2eq ha^{-1})				Total GHG emissions (kg CO_2eq ha^{-1})	C-footprint (kg CO_2eq kg dry product^{-1})
		Fertilisers application[1]	Crop residues decomposition	Production of N, P, K fertilisers/PPPs/ seeds	Field crop operations		
A1	ACT	2687	150	1637	667	5141	0.24
	FERT	1385	150	384	645	2563	0.12
	ROT	3336	510	677	1058	5581	0.19
B1	ACT	2347	196	861	1222	4627	0.23
	FERT	1857	196	679	1211	3944	0.20
	ROT	2232	306	359	1715	4612	0.21
B2	ACT	2347	403	861	1107	4719	0.46
	FERT	1755	403	583	1096	3838	0.38
	ROT	2229	404	359	1632	4612	0.33
C1	ACT	3995	360	1260	844	6460	0.32
	FERT	2317	360	250	816	3747	0.18
	ROT	4354	535	182	1438	6663	0.29
D1	ACT	2150	89	1259	945	4443	0.30
	FERT	1400	89	774	1194	3744	0.21
	FERT1	1249	89	774	880	2992	0.20
D2	ACT	2124	89	1259	964	4436	0.30
	FERT	1385	89	774	964	3211	0.21
	ROT	3706	441	1301	1493	6997	0.33
D3	ACT	1775	89	1259	574	3697	0.25
	FERT	1117	89	774	569	2549	0.17
E1	ACT	1344	233	216	1041	2838	0.15
	ROT	3454	450	902	1647	6453	0.20

[1]Includes direct and indirect N_2O emissions from N fertilisers and CO_2 emissions from urea and lime applications.

Tab. 3 - Total GHG emission and C-footprint of maize-based cropping systems under the three scenarios.
Tab. 3 - Emissione totale di gas a effetto serra e impronta di carbonio dei sistemi maidicoli per i tre scenari.

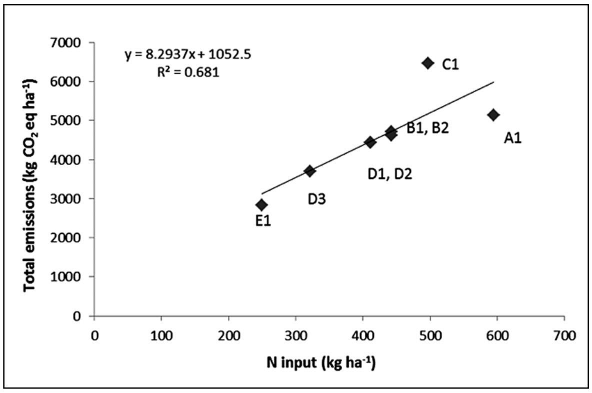

Fig. 1 - Total GHG emissions from maize fields as affected by the N amount applied with inorganic and organic fertilisers (ACT scenario).
Fig. 1 - Emissioni totali di gas a effetto serra da appezzamenti coltivati a mais in relazione all'azoto, applicato con fertilizzanti minerali e organici (scenario ACT).

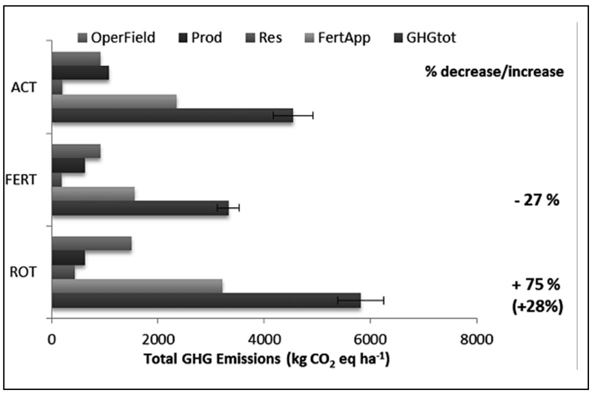

Fig. 2 - Total GHG emission and its main components of maize-based cropping systems under the three scenarios (FertApp: emission from fertilisers application, Res: emission from residue decomposition, Prod: emission from production factors manufacturing, OperField: emission from agronomic operations on fields). The percent variation describes the comparison between FERT vs. ACT, and ROT vs. FERT. In brackets is reported the relative change from ACT to ROT.
Fig. 2 - Emissione totale e dettagliata nelle sue componenti di gas a effetto serra dai sistemi maidicoli per i tre scenari. (FertApp: emissione dovuta alla distribuzione di fertilizzante, Res: emissione dovuta alla decomposizione dei residui, Prod: emissione dovuta alla generazione dei fattori di produzione, OperField: emissione dovuta alle operazioni agronomiche di campo). La variazione percentuale si riferisce al confronto tra FERT e ACT e tra ROT e FERT. In parentesi è riportato il confronto tra ACT e ROT.

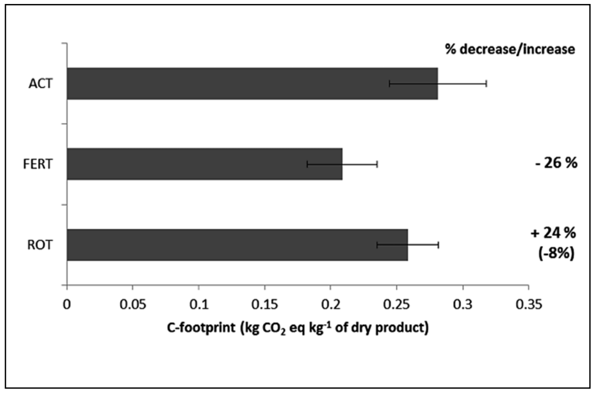

Fig. 3 - Carbon footprint of maize-based cropping systems under the three scenarios. The percent variation describes the comparison between FERT vs. ACT, and ROT vs. FERT. In brackets is reported the relative change from ACT to ROT.
Fig. 3 - Impronta di carbonio dei sistemi maidicoli per i tre scenari. La variazione percentuale si riferisce al confronto tra FERT e ACT e tra ROT e FERT. In parentesi è riportato il confronto fra ACT e ROT.

emissions, ranging from 700 to 1220 kg CO_2eq ha^{-1}. Sowing, PPPs and inorganic fertilisers application less contributed than manure application, which accounted for 18% of emissions from all field operations, on average. Tillage operations (except for E1, where minimum tillage techniques were adopted), irrigation, harvest operations and transportation of products from fields to farm were responsible of the greater contribution to GHG emission. On average, the effect of crop residues decomposition was limited around to 4.5%.

The C-footprint of SM ranged from 0.15 to 0.32 kg CO_2eq per kg of dry product, whereas the GM one, was equal to 0.46 kg CO_2eq per kg of dry product because of its lower crop yield (Tab. 3 and Fig. 3). These values were directly proportional to GHG emissions, but they were also affected by crop yields. In fact, considering the fields cropped with SM, the lower emission of D1, D2 and D3 (in comparison with A1 and B1), corresponded to higher values of C-footprint. This occurred because the lack of irrigation water in the farm D, caused a decrease of SM yield by 30%, compared to irrigated fields in farms A and B.

3.2. Effects of the alternative N managements

Under FERT scenario the use of N from inorganic fertilisers was reduced by 29% ranging from -17% (B1) to -44% (A1) (Tab. 1). Therefore, the GHG emissions decreased with the same magnitude (around 27%, Fig. 2) in comparison with ACT. The maximum reduction was detected in A1 and C1: from 5141 to 2563 and from 6460 to 3747 kg CO_2eq ha^{-1}, respectively. The emission due to the production of inorganic N fertilisers was the component most influenced by the alternative management: its reduction was, on average, by 50% with a maximum in A1 and C1 (almost 80%). On the opposite, the decrease of the emission from field operations was lower than 3%. The C-footprint in

FERT scenario had an average of 0.18 and 0.38 kg CO_2eq per kg of dry product for MS and GM, respectively. It was decreased by 26%, because emissions were reduced while the maize yields remaining unchanged.
Changes introduced in ROT had a significant effect on GHG emissions (Fig. 2). They were around 6000 kg CO_2eq ha^{-1} and they almost doubled the values estimated in FERT and ACT in the E1 case. This was due to the use of mineral N for balancing the low apparent N recovery of organic fertilisers applied on autumn-winter crops. Where winter wheat and triticale for silage were introduced (A1, D3 and E1), the increase of N input was greater in comparison with fields where Italian ryegrass was preferred, due to its lower N requirements. The double cropping systems influenced also emission from residue decomposition and field operations: they increased from 183 to 440 and from 890 to 1500 kg CO_2eq ha^{-1}, respectively.
The mean C-footprint in ROT scenario was 0.24 and 0.33 kg CO_2eq per kg of dry product for SM and GM, respectively: the increase was lower than GHG emissions because of the high yield potential of the double cropping systems. Such effect was evident in the case of GM in B2 where the C-footprint decreased compared to FERT.

4. DISCUSSION

4.1. Contribution of maize production to GHG emissions

Results showed that maize production intensively managed in Lombardy region can lead to the release of high GHG emissions. However, the high yield potential of maize crop achieving under current management determined low C-footprint values, compared to other cereal crops such as winter and spring cereals (Hillier *et al.*, 2009; Gan *et al.*, 2011a, b; Rajaniemi *et al.*, 2011).
The most substantial contribution to GHG emissions and C-footprint was given by the use of N. Emissions from the production of inorganic fertilisers and from direct and indirect N_2O released after N application accounted for, on average, the 67% with maximum values of 76 and 81% in C1 and A1, respectively. Results are in agreement with those obtained by Ma *et al.*, (2012) from a 19-year experimental dataset for maize crop, where production and application of N fertilisers accounted for values ranging from 68% to 84%. Starting from census data at the county level for Ontario, Jayasundara *et al.*, (2014) estimated that the 72% of total GHG emissions of maize production were associated with N inputs. Similar values were also registered for different arable crops (e.g. legumes, winter and spring cereals, oilseed crops) cultivated in various areas of the world (Hillier *et al.*, 2009; Mhamuti *et al.*, 2009; Cheng *et al.*, 2011, 2012; Gan *et al.*, 2011a, b; Rajaniemi *et al.*, 2011).
Data reported in Fig. 1 show the relation between fertilisers N rates and GHG emissions. The linearity of the relation is not detectable, as clearly as found by Ma *et al.*, (2012) for maize and Hillier *et al.*, (2009) and Cheng *et al.*, (2011) for arable crops. In fact, the R2 value of 0.68 can be referred to the strong influence of weather conditions during the growing season. Though the greatest N dose was applied in A1 (around 600 kg ha^{-1}) the lowest P/E ratio (0.45) limited the emissions, as well as the wettest condition of C1 (P/E = 0.78) determined the highest emissions. The magnitude of direct N_2O emissions is affected by site-specific features, particularly soil attributes and management practices, N availability and soil water content which regulates soil aeration status (Rochette *et al.*, 2008). The choice of using the method proposed by Rochette *et al.*,(2008) to estimate N_2O emission factor (EF), specifically developed for Canadian conditions, instead of the default value proposed by the IPCC methodology, was mainly driven by the need of reproducing the effect of the large regional soil and climatic variability. Nevertheless, N_2O emission factors used in the current work were similar to the one proposed by IPCC (2006), i.e. 0.01 and they were included in its uncertainty range (0.003-0.03). Although comparable values of N_2O emission factors have been reported by literature (Bouwman *et al.*, 2002; Adviento-Borbe *et al.*, 2007; Alluvione *et al.*, 2010; Halvorson *et al.*, 2010; Linquist *et al.*, 2012) the need for site- and source-specific estimations is confirmed.
Under ACT scenario, indirect N_2O emission from leaching and volatilisation accounted for almost one third of the emission derived from N fertilisers application. The modelling approach was specifically used to predict N leaching, being considered more comprehensive than other methods for describing different N management options over a mid-long-term period and under different pedo-climatic conditions. CropSyst allowed highlighting those differences in agronomic management, in soil type and in climate characteristics, being able to affect the performance of the simulated maize systems. The greatest leaching values were simulated at D1, D2 and D3 (167, 160, 128 kg N ha^{-1}, respectively), which showed sandy soil and elevated annual rainfall (around 1150 mm), and at A1 (195 kg N ha^{-1} of leaching), where the highest amount of N (600 kg ha^{-1}) was applied to maize. Conversely, the fine soil texture at B1 and B2, together with a more efficient use of water granted by the sprinkler irrigation method, reduced the risk of N leaching (around 40 kg N ha-1) as previously identified by Acutis *et al.*, (2000)

and Fumagalli *et al.*, (2013). To estimate ammonia volatilisation, the ALFAM model was adopted, because it has been previously demonstrated to be quite reliable to reproduce the magnitude of NH_3 emissions observed in field experiments carried out in the region (Carozzi *et al.*, 2013). Different manure dose, type and characteristics (i.e. N content, dry matter), diverse soil and climate conditions and application method were the variables considered in modelling NH_3 loss rates which ranged, on average, between the 17 and the 42% of total N applied to soil.

A relevant portion of GHG emissions was related to fossil fuel combustion during field operations. In the current work the common approach of most of the papers reviewed which include the adoption of a value of emission per hectare derived from literature, was not used. Indeed, the application of the mechanisation model allowed a more realistic estimation of the fuel consumption, as the peculiarity of each farm/field monitored, as well as diverse maize crop managements and soil types, the different size and working capacity of machinery, and the variable distance from farm to fields, can be better described.

4.2. N management for GHG mitigation in maize crop production

Since literature highlighted that N-fertilisers explain for a large portion of the C-footprint, especially in mineral form, a reduction of GHG emissions and C-footprint registered in FERT scenario (Fig. 2, 3), was expected. For example, Hillier *et al.*, (2009), found lower C-footprint in farms applying N in organic form than in farms mainly using inorganic fertilisers. Alluvione *et al.*, (2010) reported that, for maize-based cropping systems of northwestern Italy, organic fertilisers such as leguminous green manure and compost can be valuable substitutes of urea on a global warming perspective.

Under FERT scenario the contribution of N fertilisers, both as production and as field application, was, on average, decreased to 58% of the total emissions. The surplus of N in the soil induces indirect CO_2 emission, but the reduction of the amounts of N applied is not the only adoptable solution. Slow-release N fertilisers or nitrification inhibitors can additionally contribute to improve the N use efficiency (Smith *et al.*, 2008; Hillier *et al.*, 2012). The most important measure, however, is to better adjust N input to crop N demand, i.e. in most cases to reduce N fertilization. The effect of FERT scenario on direct CO_2 emission was negligible (Tab. 3) being the inorganic fertilisers distribution an agronomic practice that requires low fossil fuel consumption: it accounted for 1 to 7% of the total emissions from field operations.

Diversified cropping systems are suggested as an agronomic practice able to reduce C-footprint of cereal crop monoculture (Smith *et al.*, 2008; Gan *et al.*, 2011a, b; Ma *et al.*, 2012). In the current study, the addition of autumn-winter crops was proposed in ROT, as they are able to uptake the mineral N residue after maize harvest, thus reducing potential nitrate leaching and N_2O release. Since the double cropping system required more N supply and fossil energy (i.e. 12 GJ ha^{-1}, Fumagalli *et al.*, 2012) for winter crops, a relevant increase of GHG emission (75%) and its components has occurred (Tab. 3 and Fig. 2). The direct N_2O emissions were strongly reliant on more N availability in soil and on weather condition of the autumn-winter period, when precipitation usually exceeds evapo-transpiration (Tab. 2). Conversely, indirect N_2O emissions were reduced: the fraction lost through leaching was on average 10% of the total N applied. This value was lower compared to those registered in ACT and FERT (27 and 15%, respectively).

Under the ROT scenario, field operations were doubled and related emissions increased, on average, by 60%, as the plant litters from maize and winter crops represents an important N source for nitrification and denitrification. However, since the double cropping systems showed an higher productivity (Tab. 1) C-footprint was even lower than the one registered under ACT scenario, excepted for D2 and E1. Similar findings were pointed out by Gan *et al.*, (2011a, b) and Ma *et al.*, (2012), even if they analysed wheat and maize in rotation with legume crops which lead to a reduction in reliance on N fertilisers.

4.3. Other mitigation practices in croplands management

The work has highlighted opportunities for carbon mitigation from the adoption of better N management, even if other practices could be implemented: extending crop rotations with perennial and legume crops, reducing the reliance on plant protection products, using the conservation tillage and adopting more efficient irrigation measures. All those solutions act positively according to two main mechanisms: the reduction of the emissions and/or the increase of the C storage in the soils (Smith *et al.*, 2008). In arable land with intensive maize-based cropping systems the change of the crop rotation by introducing perennial and legume crops can be beneficial. For example, in one experimental site of northern Italy, the conversion of arable land into perennial energy crops determined a substantial soil organic carbon sequestration benefit after 7-years period for the soil layer 0.0-0.2 m (Ceotto and Di Candilo, 2011). Legume-dependent cropping systems can notably reduce the reliance of N fertilisers thus favouring the control of GHG emissions.

Furthermore, diversifying cropping system is one of the driving force for the development of diversified, equilibrated and sparse weed communities, which in turn lead to a decrease in reliance on herbicides (Fumagalli *et al.*, 2011).
The adoption of minimum and no-tillage practices could further reduce energy expenditure and therefore GHG emissions (Bertocco *et al.*, 2008). A worldwide review by Abdalla *et al.*, (2013) showed that the adoption of conservation tillage practices reduces soil CO_2 emissions, while also contributing to rise in soil organic carbon and enhancements in soil structure. This factor is crucial in intensively cultivated areas frequently characterized by a gradual impoverishment of soil organic matter. However, there are still doubts on the advantages of those practices with regards to N_2O emissions because experimental results are quite contrasting.
Under the commitment to reduce GHG emission a good opportunity could be provided by the water management. In areas like our region, water is usually applied with high amounts during the summer dry period, which leads to optimal moisture and temperature conditions for N_2O production. Therefore water-saving practices as drip irrigation, avoiding moisture excesses associated with reductions in air-filled pore space, may help to minimise the potential for N_2O emissions, while maintaining yields (Aguilera *et al.*, 2013).

5. CONCLUSION

The current study aimed at evaluating the efficiency of alternative N management as solutions in reducing C-footprint in a maize monoculture.
The method used for the estimation of C-footprint was analogous to the one available in literature. However, it was refined for a more accurate estimation of emissions, because of the site-specific and complex nature of GHG emissions from crop production and because N_2O emissions can significantly affect C-footprint results (Röös *et al.*, 2010; Whittaker *et al.*, 2013). Therefore, being available very heterogeneous dataset in term of soil type, climatic condition and maize crop management, the modelling approach was preferred to the default factors commonly use to predict N leaching, volatilisation and fuel consumption, which are strongly influenced by site-specific features. This approach can be useful when there is a need of producing a GHG emissions database at regional detail taking into account the great spatial and temporal variation of N_2O emissions. However, it is worth to recall that moving to more detailed approaches usually leads to heavier input requirements and resources.
The current maize crop production totally contributes to GHG emissions, also considering its diffusion across the utilisable agricultural area of the Lombardy region. The key contribution on GHG emissions is related to N used, suggesting that improved C-footprint can be accomplished by adopting adequate N management plans. The higher GHG emissions under the ROT scenario should not hide the potential advantages of the greater crop production of the double cropping system. Indeed, the C-footprint can be maintained lower in comparison with values registered under the ACT scenario.
In the end, the current work highlights the opportunities for carbon mitigation offered by changes on field N management, without significantly impact the yield.

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